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Comparative study on the behaviour of different infill materials for pre-fabricated fibre composite repair systems

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HIGHLIGHTS

- Constituent behaviour and mechanical properties of concrete-, shrinkage compensating cementitious- and epoxy-grout infills.
- Behaviour of GFRP tubes filled with different types of grout-infills.
- Pre-fabricated FRP composite repair system for deficient structures.
- Theoretical model development to predict the overall behaviour of composite repair systems with different infill materials.

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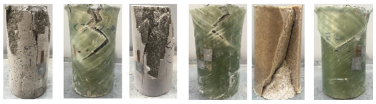
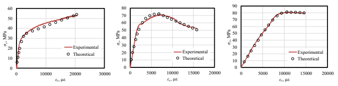
GRAPHICAL ABSTRACT



Concrete — FRP with concrete — Cementitious grout — FRP with cementitious grout — Epoxy grout — FRP with epoxy grout

Failure mode



(a) FRP with concrete (b) FRP with cementitious grout (c) FRP with epoxy grout

Experimental and theoretical axial stress-axial strain curves of grout-filled GFRP tubes

ABSTRACT

Prefabricated fibre-reinforced polymer (FRP) composite jacket is now becoming an effective repair system for deteriorating piles and columns exposed to marine environment. This system works by providing grout infills between the annulus of the existing structure and the composite jacket. Few studies are however available on the optimal grouting materials that can effectively transfer the stresses between the existing structure and the FRP jacket. This study is investigating the effect of cementitious, concrete and epoxy-based grout infills on the structural behaviour of pre-fabricated glass-FRP (GFRP) tubes. The considered grouts have compressive strength and modulus of elasticity ranging from 10 MPa to 70 MPa and from 10 GPa to 35 GPa, respectively. The experimental results showed that the behaviour of the composite repair system is highly dependent on the modulus of elasticity and the compressive strength of the grout infill. The brittle failure behaviour of the cementitious and epoxy grouts led to localised failure in the FRP repair system while the progressive cracking and crushing of the concrete infill resulted in effective utilisation of the high strength properties of the composite materials. Theoretical analysis of the overall compressive behaviour has also been conducted and showed very good agreement with the experimental results.

1. Introduction

The increasing problems of deteriorating reinforced concrete (RC) civil infrastructure have resulted in many of them becoming out of service due to safety concerns. These damaged structures need to be either replaced or retrofitted so that they can continue to remain in service. It is estimated that more than $5 billion

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annually is needed to maintain the RC bridges in each of the countries like US, Canada, and Europe [1]. In Australia, the corrosion-induced damages cost the economy more than $13 billion per year due to lost production and shutdowns to make repairs as reported by the Commonwealth Scientific and Industrial Research Organisation (cited in Cassidy et al. [2]). In most cases, it is more economical to repair the existing damaged structures than to replace them. Adopting effective rehabilitation and strengthening techniques can be economically beneficial by minimizing the off-service time of the structure, and eventually saving a significant amount of resources. Due to the limitations of the traditional rehabilitation techniques, such as concrete and steel jacketing, in terms of the material weight and the complexity of steel anchorage [3], the introduction of versatile fibre-reinforced polymer (FRP) composites for strengthening and rehabilitation of civil infrastructure has been essential and very valuable. The superior characteristics of this advanced material, such as high strength, corrosion resistance, lightweight, high fatigue resistance, high impact resistance, and durability [4], enabled it to be successfully utilised for strengthening and rehabilitating damaged and/or deteriorating concrete and steel structures, [5–8], especially those that are located in harsh environments such as marine and mining areas.

Pre-fabricated composite jackets are becoming increasingly used in repairing structures especially for under water applications. These composite repair systems are manufactured at specialised plants, thereby achieving high quality and uniformity. Moreover, they can be easily installed at site by placing the jacket around the damaged structure and serving as a permanent formwork. An appropriate grout is then placed to fill the gap between the jacket and the existing structure. The pre-fabricated FRP jacket provides protective shield and induces lateral confining passive pressure, which eventually strengthens the damaged structure. Lopez-Anido et al. [9] proposed a repair system utilizing FRP shells with two different types of grouting systems, cement-based structural grout and expanding polyurethane chemical grout, to provide protection and structural restoration for deteriorated wood piles. Williams (cited in Manalo et al. [10]) utilised pre-fabricated FRP pile jackets consisting of chop strands and woven mats impregnated with epoxy resin in the rehabilitation of New York City waterfront structures to restore its structural strength. A 3/8″ lightweight stone concrete was utilised as the grout infill to prevent the weight increase that could cause structural damage to the pier. Vijay et al. [11] used pre-cured FRP shells for encasing and rehabilitating the water-submerged steel H-piles of a bridge in the USA. The space between the FRP shells and the steel piles was filled with self-consolidating concrete to strengthen and protect the piles from further deterioration. Considering the behaviour of the repair system components, Shamsuddoha et al. [12] highlighted the effectiveness of using FRP composites and grout infills for steel pipeline repairs. In these applications, the repair systems have been successfully implemented by providing grout infills between the annulus of the existing structure and the prefabricated composite jackets.

The effectiveness of the pre-fabricated FRP jacket in repairing damaged or deteriorating structures is highly dependent on the performance of the grout infill. The grout plays a vital role in transferring the stresses between the core structure and the external FRP jacket to develop the composite action [13]. The compressive strength and modulus of elasticity are the two most important mechanical characteristics of the grout that affect its functionality in terms of load transferability and effective utilisation of the FRP system [11,12]. Sum and Leung [13] conducted a numerical analysis on a composite sleeve and epoxy grouts over a pipe subjected to internal pressure. The results indicated that a stiffer epoxy grout is preferable because it is more effective in stress transfer and makes the repair system act compositely. The bond between the grout and the FRP jacket is another factor that affects the efficiency of the FRP repair system because any discontinuity and/or voids would lead to generating non-uniform stresses onto the FRP jackets that could lead to premature failure [14]. The grout is necessary to assure a full contact between the system components as it provides a smooth bed for the FRP jacket and refill of the damaged profile of the existing structure [12]. Moreover, it is essential when shape modification is required, i.e. modifying the original structure from square/rectangular to a circular section for better confinement [15,16].

A number of studies have used several types of grouts as infill for the pre-fabricated FRP repair system [9,11,17–20]; however, these studies did not consider the structural contribution of the grout infills. There is a need therefore to have a better understanding on the mechanical properties of the grout infills and how they affect the stress development on the composite repair system. In this study, the properties of three different grout materials and the structural behaviour of a FRP repair system filled with different grouts are evaluated. The results of this study provide information on the important characteristics of the grouting materials that will be useful to effectively utilise the inherent properties of the pre-fabricated composite repair systems.

2. Experimental program

The material properties and procedures employed in the study are presented and discussed in this section.

2.1. Material properties

2.1.1. Infills

Three different types of infills were considered in this study: (1) concrete-grout infill, (2) shrinkage compensating cementitious-grout infill, and (3) epoxy-grout infill. These grout infills were selected based on their market availability and current industry practice, with taking into consideration the compressive strength and elastic modulus of the infills. For the concrete-grout infill, three different compressive strength grades, i.e. Grade 1, Grade 2 and Grade 3, of commercially available normal concrete made up of Portland cement, water, sand, and gravels with maximum aggregate size of 10 mm were used. The shrinkage-compensating cementitious grout was made up of cement powder with 0.3 mm maximum particle size. Its shrinkage-compensating feature allowed the final product to be volumetrically stable during the initial stage of curing and prevented cracking due to plastic shrinkage. Following the recommended procedure in the technical data sheet [21], a water-to-cement weight ratio of 0.175 was adopted to obtain a flowable grout that suits filling applications while avoiding the formation of voids. A high strength chemical epoxy grout [22] was used in this study and consisted of two main components; the polyurethane (Part A) and binder (Part B). After the proper mixing of these components, special graded aggregate and fillers for epoxy compounds were added to the mix to produce the desired grout mortar.

2.1.2. GFRP tubes

Fig. 1 shows the prefabricated glass-fibre-reinforced polymer (GFRP) tubes that were manufactured using the filament winding method with E-glass fibres and vinyl ester resin. Experimental approaches in accordance with the ISO 527-1:1995 [23] and ISO 14126:1999 [24] were adopted to ascertain the tensile and compressive properties of the GFRP tubes. The test coupons were cut from the large GFRP laminates, with the same lay-up and composition as the GFRP tubes, using the water jet cutting machine. The results of the material characterisation are listed in Table 1. As can be seen from the table, the GFRP tubes had average tensile strength (f_f) and tensile modulus (E_f) equivalent to 297 MPa and 24 GPa, respectively. The compressive strength (f'_f) and compressive modulus (E'_f) on the other hand, were equal to 180 MPa and 30 GPa, respectively.

Burnout test was also conducted, in accordance with ISO 1172-96 [25], to determine the fibre content ratio and fibre stacking sequence of the GFRP tubes. The test revealed that the GFRP tube material has 67.6% fibre content by weight. As depicted in Fig. 2, the GFRP tube had a stacking sequence of −45°/+45°/−45°/+45° with respect to the hoop direction. Such configuration is effective in managing multi-axial stresses and in achieving more ductile behaviour at failure [26,27].

2.2. Test specimens

Three replicates were prepared for each type of specimen, yielding a total of 36 specimens including three (3) hollow GFRP tubes, fifteen (15) infill cylinders, fifteen (15) grout-filled GFRP tubes, and three (3) filled GFRP tubes with the internal surface roughened with epoxy and 5 mm size course aggregates. The specimens were cured and tested after seven days.